

On the Occurrence of Eclogite in Western Norway*

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Abstract. Recent experimental data show that eclogites may form in the crust under conditions where total pressure exceeds water pressure. The regional distribution of eclogites in Western Norway and their association with crustal rocks makes their formation in the crust the most attractive hypothesis. Before a mantle origin should be assigned to any rock within this eclogite and garnet peridotite area it should be demonstrated that their country rocks are in a metamorphic state incompatible with the load pressures required for eclogite stability. Criteria for ascertaining eclogite formation in the crust are discussed.

Introduction

At the present time there is intense interest in the nature of the upper mantle. Goldschmidt (1922) suggested that eclogites could be possible upper mantle constituents. The feasibility of this suggestion has been amply verified by experimental studies of the basalt-eclogite transition. It has also been shown (e. g. Bearth, 1959) that basaltic rocks of surface or near-surface origin can be depressed in the crust and become eclogites. Thus when an eclogite is encountered in a metamorphic terrain the question must arise: "Is this rock formed in the crust or has it been introduced from the mantle?". Because the upper mantle is in fashion, there is perhaps a tendency to mantle-ize, if possible. Today, there is an increasing body of evidence suggesting that convective and gravitational forces may drag crustal materials deep into the mantle. Similarly, there have long been suggestions of tectonic emplacement of upper mantle materials in orogenic regions (de Roever, 1957).

Recently, we visited a number of eclogite and garnet peridotite occurrences in Romsdal, Sunnmøre and Nordfjord, Western Norway. Some of these were included in Eskola's (1921) classical studies on eclogites. Most recent studies of these eclogites have interpreted them as metamorphosed dolerites, gabbros and other crustal rocks (Gjelsvik, 1952; Hernes, 1954; Kolderup, 1955, 1960; Schmitt, 1963, 1964; Bryhni, 1966) but others have argued for tectonic emplacement of upper mantle eclogite and garnet peridotite into crustal gneisses (O'Hara and Mercy, 1963; Lappin, 1966; Carswell, 1968 a, b). Our attention was focussed on the immense difficulty of proving that these eclogites were indeed upper mantle or tectonically emplaced.

This problem has partly arisen from lack of clear data concerning the conditions of formation of eclogites and particularly from an erroneous conviction that the

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pressures required for eclogite stability are only attained within the upper mantle. Recent data clarify these points. First, we know that eclogites do form from crustal materials and the metamorphosed pillow lavas described by Bearth (1959) are a striking example. Second, experimental studies have shown that at moderate temperature, eclogites can form from rocks of appropriate composition, at pressures well within the crustal range (Green and Ringwood, 1967). If we consider that crustal thicknesses of 45 km are not uncommon and may reach 60 km in active orogenic regions, then metamorphic assemblages formed at load pressures of 15–17 kb may be expected in crustal materials. Eclogites could be stable in dry basaltic rocks at such pressures at temperatures below 900°C. On the other hand partial melting of crustal materials could occur at these conditions if hydrous minerals are present.

Eclogite and Amphibolite Relationships

It is of considerable importance to understand the stability of eclogite mineralogy relative to amphibolite. Green and Ringwood (1967) and Essene and Fyfe (1967) predicted that at sufficiently high $P_{\text{H}_2\text{O}}$ the assemblage garnet + omphacite + water (eclogite) would be stable relative to amphibole. Preliminary experiments by Essene *et al.* (1969) show that at a temperature of 700°C, a pressure ($P_{\text{H}_2\text{O}} = P_S$)¹ of 21 ± 3 kb is required for the breakdown of amphibolite to yield eclogite. Fyfe and Fry (1969) also considered the stability of eclogite in wet rocks where $P_{\text{H}_2\text{O}} = P_S$. Their analysis was based on data concerning the stability of amphiboles and the gabbro-eclogite transition. If these data are treated thermodynamically it is possible to construct a phase diagram for the amphibolite → eclogite transition which shows that if $P_{\text{H}_2\text{O}} = P_S$, eclogites cannot form in any normal crust but would be replaced by amphibolite or amphibole-rich assemblages.

From both the experimental and thermodynamic data, it can be said with some certainty that if eclogites are to form in the crust we must have conditions of relatively dry rocks or $P_{\text{H}_2\text{O}} < P_S$ and a total pressure in accord with the gabbro-eclogite transition (Fig. 1). How and when the transition occurs will depend on all the factors involved in a solid state reaction requiring diffusion over distances related to the grain-size and fabric of the original basaltic materials. Studies of Fe/Mg distribution coefficients between garnet and clinopyroxene (Banno and Matusi, 1965; Lovering and White, 1969) suggest that eclogite formation occurs over a wide temperature range and thus probably over a range in pressure. On the basis of these Fe/Mg distribution coefficients, absence of glaucophane and lawsonite and presence of kyanite and calcic hornblende, the Norwegian eclogites are inferred to have crystallized at higher temperatures than for example, the Californian eclogites.

Country Rocks

Before an eclogite found in the crust is given a mantle origin, it is necessary to first consider whether or not the host crustal rocks exhibit a mineralogy which would indicate pressures significantly lower than those required for the basalt-

¹ P_S = pressure on solid phases. P_F = pressure on fluid phase if this is present. $P_{\text{H}_2\text{O}}$ = water pressure.

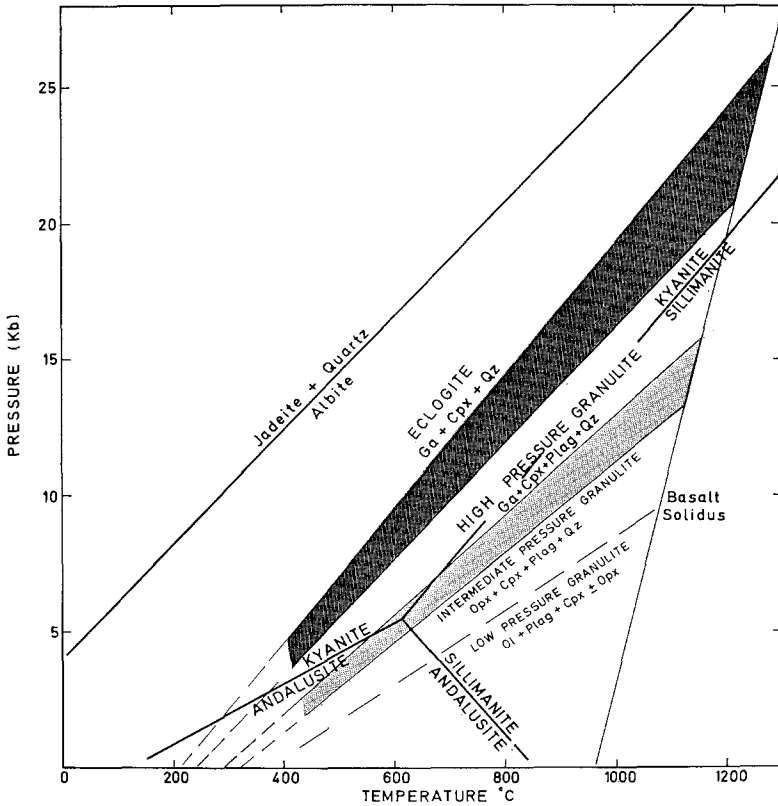


Fig. 1. Comparison of the gabbro to eclogite transformation in basaltic rocks (Green and Ringwood, 1967) with the stability fields of kyanite, sillimanite and andalusite (Richardson *et al.*, 1969). The heavily shaded area expresses the PT interval over which a spectrum of basaltic rocks will transform from the garnet + clinopyroxene + plagioclase assemblage to garnet + omphacite \pm quartz. The lightly shaded area represents a similar transition interval between the low pressure orthopyroxene + plagioclase granulites and high pressure granulites

eclogite transition, taking into account that the enclosing rocks may represent a much wetter metamorphism. In this connection it is of considerable interest to compare the kyanite-sillimanite curve with that of gabbro-eclogite (Fig. 1). It will be noted that these are similar in slope and position. It would be surprising to find eclogites in sillimanite-zone metamorphic rocks, but eclogite or high pressure granulite ($ga + cpx \pm plag \pm quartz$) assemblages should be typical of dry basic rocks in kyanite-zone metamorphic rocks.

In Western Norway kyanite has occasionally been reported in rocks associated with eclogites (Schmitt, 1963; Lappin, 1966; Bryhni, 1966; Green; unpublished). Sillimanite occurs in some of the gneisses but Schmitt (1963) demonstrated that, in Hareid, it postdates eclogite formation and locally replaces kyanite. Kyanite-bearing gneisses and eclogite are associated in Eastern Sudetes, Poland (Kozłowski, 1958) and apparently also in the Alps. In California, the association of eclogites with metasediments which have crossed the albite \rightarrow jadeite + quartz boundary

(Fig. 1) demonstrates that in this area also the country rocks have been well within the eclogite stability field.

In Western Norway we were impressed by the frequency of occurrence of eclogite or garnet-bearing coronites. In fact, over a very wide area, it seems that almost every basic rock contains a pyroxene-garnet assemblage, often partially destroyed by later amphibole formation. There may be more than one period of basaltic intrusion in this area (bodies range from syn-tectonic or pre-tectonic lenses and boudins to clearly intrusive late-tectonic or post-tectonic sheets). It is also as yet uncertain whether the coronites represent cooling of an igneous body into the high pressure granulite field or through this field into the eclogite stability field (Fig. 1). However, it is apparent that reactions have occurred on a regional scale appropriate to load pressures in excess of 10 kb. In this environment, it is unnecessary to ascribe other eclogite and garnet peridotite lenses to a mantle origin, their mineral assemblages may be in no way incompatible with their country rock environment. In an excellent, detailed study of the Eiksundsdal Eclogite Complex and its associated country rocks, Schmitt (1963, 1964) demonstrated a common origin for interlayered eclogites and garnet peridotite and provided evidence for their initial crystallization as olivine, pyroxene and plagioclase-bearing basaltic accumulates, later metamorphosed along with their country rock environment, under high pressure conditions.

Advocates of an upper mantle origin for the eclogites and garnet peridotites have emphasized the "tectonic contacts" against the enclosing gneiss. However, if dry basic rocks are enclosed in wetter metasediments their mechanical or deformational properties will not be similar. This will make description of tectonic features indicating tectonic emplacement a matter of extreme difficulty. For instance, do shear zones on serpentinite margins always imply large scale tectonic movements or do they reflect large differences in the mechanical properties of the rocks being deformed? There are excellent examples showing that such differences are highly significant in deformation and in Western Norway it should be emphasized that boudin structure and lenticular form of contrasted rock types are common within the gneiss and are not a characteristic of eclogite or peridotite alone.

The Role of Partial Melting in Eclogite-Bearing Terrains

Having recognised that crustal eclogites would require the involvement of dry basaltic materials one might well ask what would be the ideal situation for the production of eclogites? Clearly deep burial of a massive pile of dry basaltic material would be appropriate. Free movement of water vapour, i.e. a permeable rock column, would likewise provide a mechanism by which $P_{H_2O} < P_S$ (Yoder, 1955), but it is improbable that such permeability exists during a deep metamorphism or could cause a sufficient difference in the variables. With respect to Norwegian rocks one can suggest another model. It is possible that here one is working with a very old basement which has been through a cycle of partial melting and hence desiccation. After such a cycle or during the late stage of such a cycle, water will be present only in minerals such as biotite and hornblende. If such a basement were intruded by basic dykes, conditions could be unfavourable

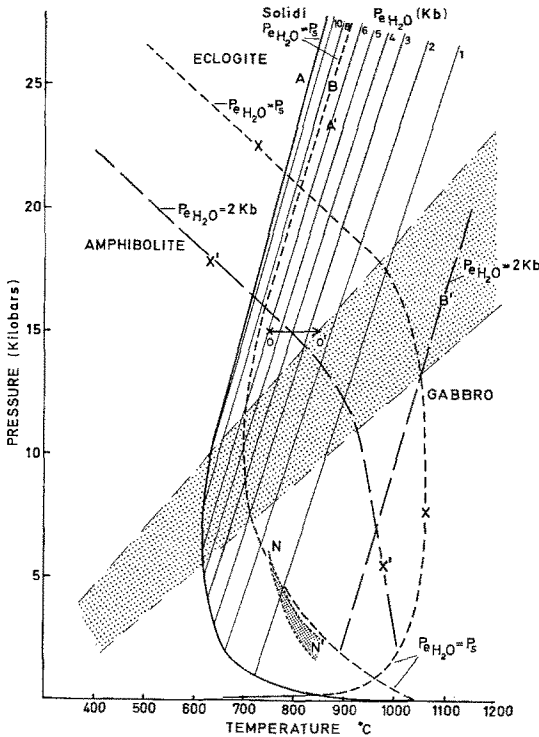


Fig. 2. Diagram illustrating the possible effects of partial melting in a mixed amphibolite + feldspathic gneiss terrain under conditions of $P_{H_2O} < P_s$. Solid lines refer to feldspathic gneiss, dashed lines refer to basic compositions. Lightly stippled area: gabbro \rightarrow eclogite transformation in "dry" basaltic compositions ($P_{H_2O} = 0$). A solidus for feldspathic gneiss (plagioclase + K-feldspar + quartz + biotite \pm amphibole) for $P_{H_2O} = P_s$. A' solidus for $P_{H_2O} = 6$ kb. B solidus for amphibolite (hornblende + quartz \pm plagioclase \pm garnet \pm biotite) for $P_{H_2O} = P_s$. B' solidus for $P_{H_2O} = 2$ kb. X maximum stability limit of amphibole from amphibolite B for $P_{H_2O} = P_s$. X' stability limit for $P_{H_2O} = 2$ kb. O—O' Postulated path of metamorphic terrain during prograde, metamorphism in deeply buried "basement". N—N' Variation in P_{H_2O} in a low melting liquid from gneiss A during prograde metamorphism O \rightarrow O'. The positions of solidi, amphibole breakdown etc. are estimated from data by Yoder and Tilley (1962), Essene *et al.* (1969), Lambert and Wyllie (1968), and Green (unpublished data). Lines of equal water pressure (A', B' etc.) have been drawn as straight lines but in real systems will be slightly curved

to amphibolite formation, but given sufficient burial, could be favourable for eclogite formation ($P_{H_2O} < P_s$; Figs. 1, 2). These conditions would particularly apply to an older basement involved in a second orogenic and metamorphic episode. The possibility of partial melting under these high pressure conditions, water being supplied by destruction of hornblende and biotite, would also strongly influence the P_{H_2O} conditions. In Fig. 2 we consider metamorphism and partial melting of a basement including feldspathic gneiss and amphibolite in which water is present in hornblende and biotite. Point O represents a condition along a geothermal gradient which the metamorphic terrain attains during deep burial. At O, $P_s = 15$ kb, $T = 750^\circ$ C and P_{H_2O} is some value determined by the phase assem-

blages, particularly the hornblende and biotite. O lies at a temperature higher than the solidus for $P_{\text{H}_2\text{O}} = P_S$ so that any breakdown of biotite or hornblende solid solutions to anhydrous phases and water will immediately cause melting. The condition for the reaction biotite + hornblende + etc. \rightarrow melt + etc. may be exceeded in the feldspathic, but not for the different phase composition and assemblage of the amphibolite.

The melt formed at $T = 750^\circ \text{C}$, $P_S = 15 \text{ kb}$, $P_{\text{H}_2\text{O}} \simeq 6 \text{ kb}$ will contain approximately 10% water (Burnham, 1967, p. 65) and, if the gneiss originally contained 1% water, then the degree of melting accompanying the destruction of the hydrous phases is $\simeq 10\%$. At this point the magma may segregate and migrate, becoming essentially an independent chemical system open to reaction with surrounding rocks, or it may remain as a dispersed fluid phase ($P_S = P_F > P_{\text{H}_2\text{O}}$) within the chemical system defined by the feldspathic gneiss bulk composition. In either case, temperature increases ($0 \rightarrow 0'$) will lead to an increase in the amount of partial melting of anhydrous silicates, residual from the reaction: biotite + hornblende + etc. \rightarrow melt + etc. If the volume of the melt increases from 10 to 20% of the initial gneiss, or doubles in volume by reaction with enclosing rocks, then the water content will drop to 5%, giving, at $T = 850^\circ \text{C}$, $P_S = 15 \text{ kb}$ a value of $P_{\text{H}_2\text{O}} \simeq 1\text{--}2 \text{ kb}$ (Burnham, 1967, p. 37). Such estimates are rough. For instance, if there is no segregation of magma from its initial source rock, then $P_{\text{H}_2\text{O}}$ cannot decrease below 2.5 kb at 850°C or the melt will crystallize (Fig. 2). Similarly, any breakdown of hydrous phases in neighbouring rock types may increase the water content and partially counteract the effect of increased partial melting. Nevertheless, it is clear that partial melting of crystalline rocks containing small amounts of water may lead to low values of $P_{\text{H}_2\text{O}}$ yielding a "buffered" condition of $P_S = P_F > P_{\text{H}_2\text{O}}$ (see also Burnham, 1967, pp. 64—72.) The approximate variation in $P_{\text{H}_2\text{O}}$ in the feldspathic gneiss as temperature increases from 750 to 850°C is shown in Fig. 2 by the shaded area N-N'. The resultant decrease in $P_{\text{H}_2\text{O}}$ during the partial melting may make amphibole unstable in neighbouring amphibolite leading to breakdown to eclogite + a small fraction of water-rich melt.

This point can be put in another way with respect to Fig. 2. Consider a region of mixed granitic-basaltic materials at a pressure such as 15 kb and 900°C where $P_{\text{H}_2\text{O}}$ is controlled by the vapour pressure of minerals such as hornblende and biotite. Let us assume that $P_{\text{H}_2\text{O}}$ in the environment has some value (say 5 kb) set by the hydrates. From Fig. 2 it is obvious that both granite and basalt could melt. Granitic fractions will progressively melt until $P_{\text{H}_2\text{O}}$ reaches about 2 kb causing hydrated minerals to decompose. But as this $P_{\text{H}_2\text{O}}$ is lower than can be reached by the more basic melt this will lose water to more acid fractions and solidify. The net result is a transfer of water from basic to acid regions.

We consider that partial melting in a metamorphic terrain of low water content and mixed gneisses can effectively lower the partial pressure of water and buffer it at a low value, leading to dehydration of mineral assemblages, particularly in more refractory mafic rock types. This situation is very different from that occurring where dehydration occurs without partial melting.

In Western Norway migmatization occurs within the gneisses throughout the eclogite-bearing region. Age relations of this migmatization to the eclogite crystallization remain unknown. In particular we have observed small irregular patches

of plagioclase + hornblende + quartz (+ biotite + garnet) pegmatite closely associated with many eclogite lenses. They commonly occur in the necks of eclogite boudins or as irregular schlieren in the country rock gneiss. Such patches may have been liquids at the time of eclogite crystallization and have been undersaturated in water ($P_{\text{H}_2\text{O}} < P_f$). If during a later temperature drop in the area, these bodies of liquid began to crystallize, then their $P_{\text{H}_2\text{O}}$ would rise, causing crystallization of hornblende and minor biotite from the liquid and local hydration with growth of amphibole in neighbouring eclogite. This explanation may account for the presence in some eclogites of large poikiloblastic hornblende whose form suggests replacement of garnet and pyroxene at an early stage, differing markedly from the kelyphitic and patchy amphiboles of later alteration stages.

Concluding Statement

Before a mantle origin is assigned to eclogite and garnet peridotites associated with crustal rocks, it is quite necessary to show that the crustal rocks are in a metamorphic state incompatible with the load pressures required for eclogite stability. In this respect it is of paramount importance to distinguish mineralogical differences due to differences in $P_{\text{H}_2\text{O}}$ or other chemical characteristics from differences in P_S and T . Examination of the Western Norway eclogites on this basis has not yet been carried out but there is fragmentary evidence strongly suggesting the regional extent of high pressure metamorphism characterized by $P_{\text{H}_2\text{O}} < P_S$ and pressures appropriate to eclogite and garnet peridotite metamorphism of pre-tectonic, syntectonic and late tectonic gabbroic and ultramafic rocks.

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